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Dating Neurological Injury

A Forensic Guide for Radiologists, Other Expert Medical Witnesses, and Attorneys

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Preface

Why do we need a book on the dating of neurological injury? Over the last decade, I have personally reviewed more than 80 medical–legal cases related to neurological disease in which some aspect of the case involved imaging technology. Many cases – in clinical situations, such as alleged birth-related hypoxia or ischemia, surgically-related injuries, or trauma-induced spinal cord or brain substance abnormalities, for example – shared the need both to detect the presence of an injury and to date the time it occurred. While a minority of cases involved the misdiagnosis of an aneurysm, a delayed diagnosis of spinal fracture, or orbital injury during a surgical procedure, the large majority of cases used modern imaging, first to detect if an injury had occurred to the brain substance or the spinal cord (collectively referred to as the central nervous system) and second to determine, if an injury did occur, at what time it occurred.

In a medical–legal setting, the interplay between the radiographic findings and the clinical findings has several possible scenarios. On one extreme, the imaging findings may be so unequivocal that no doubt exists as to what occurred and even little doubt about when it occurred. On the opposite extreme, the radiologic findings may be either completely noncontributory or may show that an event occurred but offer no insight into when it occurred (and hence its proximate cause). In between is a gray area in which the clinical history can often be very helpful in delineating the imaging findings to more accuracy and specificity; and the reverse may also be true, i.e., that the radiology may help clarify the clinical picture. My hope is that this text will be helpful in all situations – from those in which radiology is clear, to those in which the findings are less certain though still present – by providing guidelines and principles for the application of imaging findings.

The realm of this book is not to discuss specific clinical and radiographic findings at the level of the medical expert radiologist, nor is it intended to be an exhaustive treatise on recognizing the imaging signs of brain abnormality, as that is more appropriately covered in a textbook on medical imaging. Rather, I intend to represent in a systematic fashion the principles involved in the interpretation of images of the central nervous system specifically in a medical–legal setting where concern exists about the occurrence and timing of an injury.

What this book uniquely presents is a new way to approach the dating of neurological injury as imaged by modern computed tomography (CT), magnetic resonance (MR), and ultrasound (US). Throughout the text, I describe dating by two distinct but complementary methods. In the first, I explain how knowledge of the dynamic and rapidly changing imaging findings that occur in the first few weeks after an injury permit dating in this acute period. In the second, I illustrate how patterns of injury with specific features can date with some accuracy the time an injury occurs, which may be much earlier than the time when the image was obtained. This tends to be dating that occurs in the chronic period.

Chapters are presented in a logical progression beginning with the general appearance of normal brain and progressing to the way abnormalities manifest themselves on CT, MR, and US images. The emphasis in these discussions is on the appearance of edema and of hemorrhage, as these two findings are the brain's most common response to injury. I discuss the role of contrast in central nervous system (CNS) imaging, which will lead to a discussion of how infarction (death of tissue), ischemia (decreased blood flow to tissue that is still potentially alive and recoverable), and hemorrhage change with time as seen on CT, MR, and US images, and a dialog of what different patterns of injury tells us about the mechanism, severity, and duration of injury. This then permits a statement of what I consider the overriding principles of image interpretation as they relate to legal matters and a frank discussion, based on everything mentioned up to this point, of what can and what cannot be said in a medical–legal setting based on the imaging findings. The last chapter is on the root causes for uncertainty in dating neurologic events from imaging studies.

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Part I Fundamentals

Part I
Fundamentals

Chapter 1
The Structure of the Normal Brain and Its Imaging Appearance

Abstract This chapter is an introduction to the anatomy and terminology necessary for understanding the remainder of the book. It presents the names of the regions and structures of the brain, the various spaces of the intracranial compartment, the significant anatomy of the major structures that surround the brain, and the spaces that contain cerebrospinal fluid both within and around the brain. Because infarctions and hemorrhage are major topics discussed later in the book, this chapter places heavy emphasis on the vessels of the brain, normal vascular anatomy of the brain, normal vascular territories, and the various means of imaging these vascular structures.

Keywords Brain • Brainstem • Cerebellum • Computed tomography (CT) • Magnetic resonance (MR) • Meninges • Neuroanatomy • Scalp • Skull • Spinal cord • Ventricles • Ultrasound (US)

Introduction

This chapter's anatomic discourse is intended to introduce to those unfamiliar with neuroanatomy the basic concepts necessary to understand the more detailed discussion which will follow. Topics to be covered in this chapter are: (1) layers of the scalp, skull, and meninges (the tissue coverings of the brain and spinal cord); (2) blood supply (arterial and venous); (3) the cerebral hemispheres; (4) the cerebellum; (5) the brainstem; and (6) the ventricles (fluid-filled cavities within the brain) and cerebral spinal fluid (CSF) dynamics. Clinicians, experts, or others with an existing, solid knowledge of neuroanatomy and the normal appearance of the brain on computed tomography (CT), magnetic resonance (MR), and ultrasound (US) may need only to skim this chapter as a review before beginning in earnest in Chap. 2. However, regardless of one's level of familiarity with these topics, individuals who are unfamiliar with the basic terminology used to describe CT, MR, and US should briefly read the first section of Chap. 2 before tackling this chapter on introductory anatomy and the imaging appearance of the brain.

Finally, before we proceed, we must briefly discuss the standard nomenclature for orientation of images. When referring to different cross-sectional images of the brain, three standard orientations are used. As a reference, if one uses a person standing, facing you, the viewer, then an axial plane is a section parallel to the floor – that is, perpendicular to the long axis that runs from the head to the feet. A coronal plane is at right angles to an axial plane and results in thin sections, as though one were viewing a small slice of the brain from the front. A sagittal plane is perpendicular to both of the previous planes and results in a thin section of the patient's brain viewed from the side (Fig. 1.1). If images of a patient are initially obtained in one plane and then used to produce images in a different plane, the second set of images is said to be reformatted.

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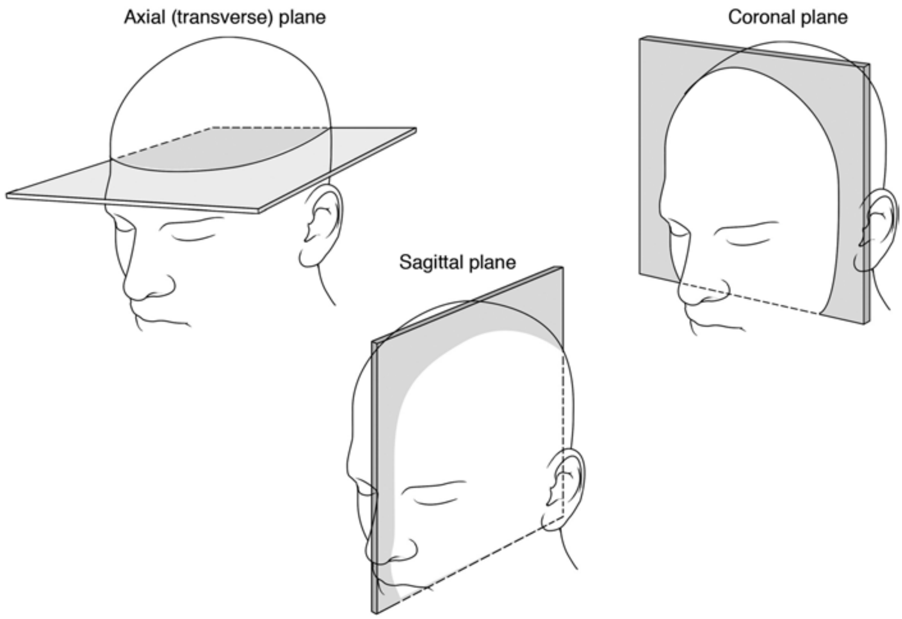

Fig. 1.1 Anatomic planes. Oblique view of the head showing standard anatomic orientation of a coronal, a sagittal, and an axial (or transverse) plane

The Layers of the Scalp, Skull, and Meninges

A discussion of normal brain and skull anatomy is best started with an explanation of the layers of tissue related to the skull, beginning most superficially and extending sequentially into the deeper and deeper tissues. Figure 1.2 is a graphical representation of the layers.

The Scalp

The scalp is the outermost layer of the tissues of the head. Beginning superficially and progressing to successively deeper tissues encountered are the skin (epidermis and underlying dermis), a layer of fat, a layer of dense fibrous tissue (the aponeurosis), another thin layer of fat, and the periosteum, covering the outer surface of the bony skull.

Clinical Note: Blood can collect between any of these layers. If it is located in the skin and underlying fat above the aponeurosis, it is termed a caput succedaneum. If located between the aponeurosis and the periosteum, it is a subgaleal hemorrhage. Lastly, if between the periosteum and the outer table, it is termed a subperiosteal hemorrhage – or, alternatively, a cephalohematoma [1].

The Skull

The cranial portion of the skull, composed of bone, has a dense outer layer – the outer table – and a second dense inner layer, the inner table. Between the inner and outer tables is the diploic space, which contains fat and myeloproliferative elements – unlike the thicker, denser bone on either side. The myeloproliferative elements are constituents of the body which produce and are the precursors of white blood cells, red blood cells, and platelets.

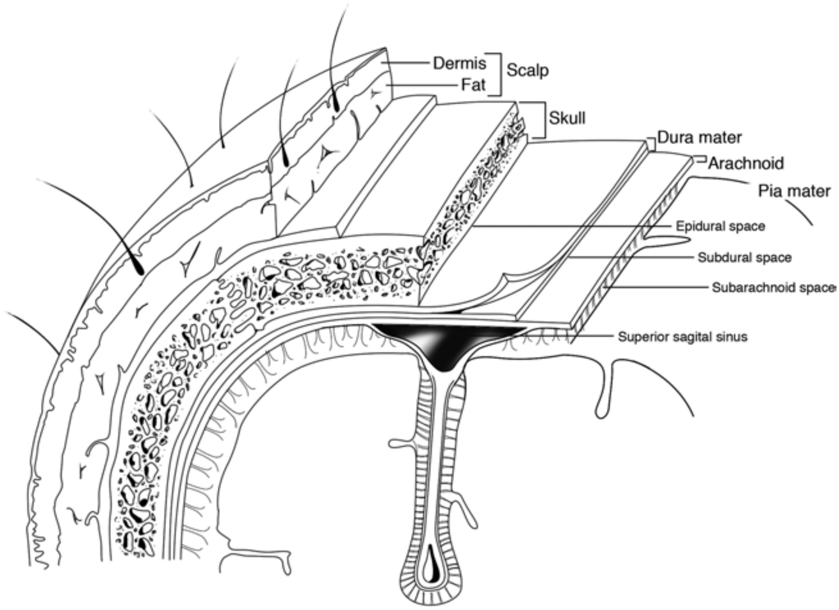

Fig. 1.2 Layers of the scalp, skull, and meninges. Intracranially, the space between the skull and the dura is the epidural space, the space between the dura and the arachnoid membrane is the subdural space, and the space between the arachnoid membrane and the pia membrane closely applied to the brain surface is the subarachnoid space. Cerebral spinal fluid (CSF) fills the subarachnoid space normally

The major bones comprising the sides and top portion of the skull are the frontal, parietal, temporal, and occipital bones. The underlying lobes of the brain take their names from the bones which overlie them. Sutures are the point of contact between adjacent bones. The paired coronal sutures are the line of connection between the frontal and parietal bones; the single midline sagittal suture is where the two parietal bones meet in the midline at the top of the skull and the posteriorly located, paired lambdoid sutures are where the occipital bone meets the parietal bone on either side. In the neonate the region in the anterior midline at the front of the sagittal suture is not yet completely fused, and this anterior fontanelle permits US examination of the brain up to about 1 year of age (when the fontanelle closes completely) (Fig. 1.3).

The Epidural Space

The epidural space is a potential space; meaning that it has the possibility of existing, but in many normal individuals, does not. It is the space between the inside of the skull (or inner table) and the endosteal layer of the dura (the outermost connective tissue covering the brain) which has produced a periosteum, which is normally closely and firmly applied to the inner surface of the skull. In order for anything to occupy this space, this periosteum must be stripped (separated) from the inner table.

Clinical Note: Blood collections in the epidural space most commonly occur as the result of a skull fracture, which ruptures blood vessels either in the skull or in the dura. As arterial pressure builds behind the blood and strips the periosteum from the inner table, a clot forms within the epidural space. Characteristically, blood in the epidural space has a biconvex shape, meaning both sides of the clot bow outward. This is due to the difficulty the clot has in stripping the dura from the inner table, so that the size of the hematoma is restricted and the margins of the hematoma are sharply defined.

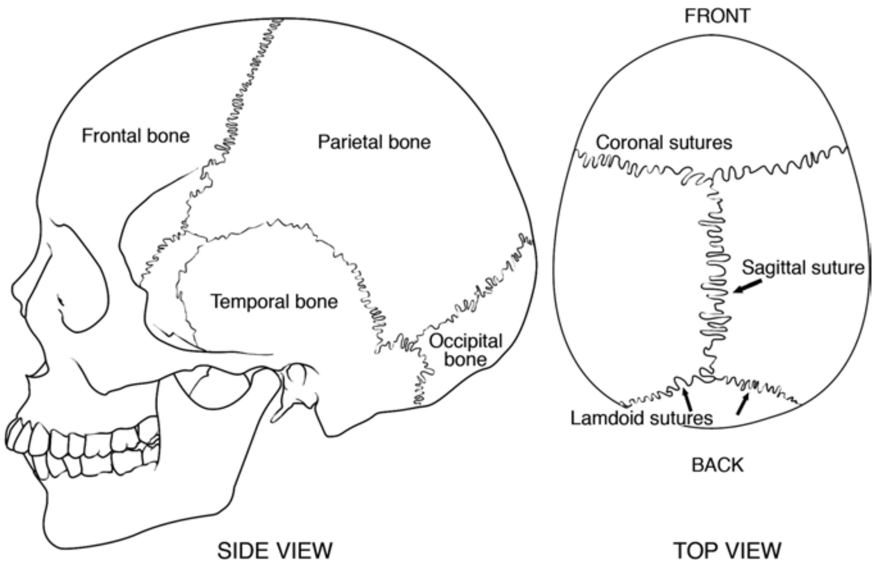

Fig. 1.3 Bones and sutures of the skull. Side and top view of the skull showing the major flat bones which make up the calvarium – the frontal, parietal, temporal, and occipital bones; and the major connecting sutures – the coronal, sagittal, and lambdoid sutures

Since the dura is very tightly applied to the skull at the coronal, sagittal, and lambdoid sutures, epidural hemorrhages rarely cross cranial suture lines (Figs. 2.12 and 2.13).

The Dura

The dura is the outermost, toughest, thickest layer of the meninges, which collectively are the three connective tissue layers that cover the brain. The meninges consist of the dura, the arachnoid membrane, and the pial membrane. The dura is further subdivided into an endosteal layer (firmly applied to the bone and producing a periosteum as described above) and a meningeal layer. These two portions of the dura are normally closely applied to each other throughout most of the inside of the skull. However, along the top of the skull and the rear of the skull on either side, the two layers separate and produce a venous drainage passage or dural sinus deep in the skull (Fig. 1.2).

The inner portion of the dura also subdivides the major compartments of the brain. The inner meningeal layer of the dura is reflected inward, toward the center of the skull and forms two principal septae. The first, the tentorium cerebelli, runs horizontally, separating the occipital lobe of the cerebral hemispheres from the cerebellum and brainstem. The second, the falx, is a midline, vertically oriented layer of meningeal dura that separates the right from the left hemisphere. This separation is partial, as a side-to-side connection remains, represented by the major white matter tract of the corpus callosum (Fig. 1.4).

The Subdural Space

The subdural space is the space between the meningeal layer of dura and the arachnoid membranes. This space is normally very small, with the potential to enlarge.

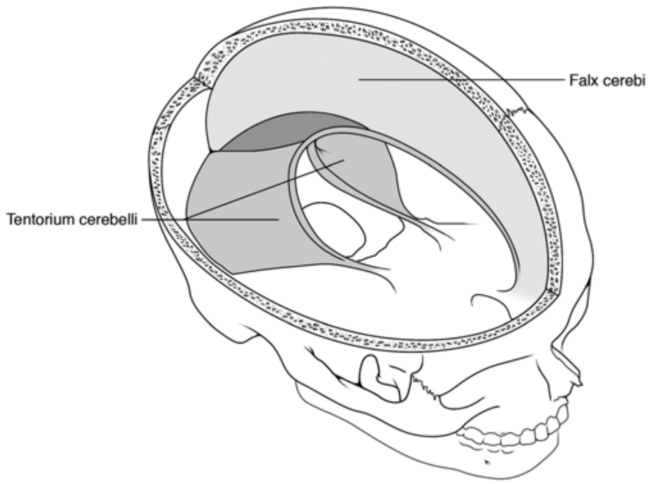

Fig. 1.4 Dura. The dura consists of an endosteal layer and a meningeal layer. The endosteal layer is applied to the inner surface of the skull and forms the periosteum. The meningeal layer is normally fused to the endosteal layer, but is separated from the latter at locations of dural venous sinuses. It is the meningeal layer that turns inward toward the center of the skull, forming the two major septae – the midline falx cerebri structure which is attached superiorly to the skull but is open inferiorly, and the horizontally oriented tentorium cerebelli which separates the occipital lobe above the tentorium from the cerebellum and brainstem below

Clinical note: Hemorrhage within the subdural space can flow more freely over the cerebral hemispheres, but it does not flow down into the sulci (troughs) between the cortical gyri (the rounded, curved linear structures on the surface of the brain). It is not limited by suture lines and has a characteristic convex/concave shape – that is, the convex side hugs the inner table and dura and the concave side faces the brain below (Figs. 2.12 and 2.13).

The Arachnoid Membrane and Subarachnoid Space

The arachnoid membrane is normally closely applied to the meningeal layer of dura. The subarachnoid space is located between the arachnoid membrane and the pia (which is closely applied to the brain surface) and is filled with cerebrospinal fluid. This space is important for several reasons. First, the arteries and cortical veins on the surface of the brain lie within this space. Second, it is the space into which aneurysms most commonly rupture. Next, it is also the space into which nonaneurysmal hemorrhage occurs, most commonly due to trauma. Finally, it is the space in which purulent material accumulates in a meningeal infection.

Clinical Note: The most common cause (occurring 80–90% of the time) of subarachnoid hemorrhage in the nontraumatic patient is rupture of an intracerebral aneurysm (a weakened portion of an artery that has abnormally ballooned) [2]. However, overall, the most common cause of subarachnoid hemorrhage is trauma, as trauma is a much more common entity than aneurysmal rupture. Therefore, the CSF can become bloody both from aneurysm rupture and from head trauma. The subarachnoid space can also be filled with inflammatory cells in cases of meningitis (infection or inflammation of the meninges) and in most cases of cerebritis (infection or inflammation of the brain). Other causes of dense CSF include proteinaceous inflammatory fluid or frank pus from a truly fulminate bacterial infection.

The subarachnoid space over the hemispheres freely communicates with the subarachnoid space around the spinal column and with the CSF within the ventricles (fluid-containing cavities within the brain) via small holes in the fourth ventricle, called the foramen of Magendie and Luschka (see Fig. 1.37).

Finally, the arterial vessels that supply the brain, as well as the cortical veins that drain blood from the brain, run within the subarachnoid space. As the incoming arterial vessels branch progressively smaller, they remain on the surface of the brain until they reach a small size, at which point they penetrate the surface of the brain, carrying with them in a circumferential fashion a contiguous extension of pia and the subarachnoid space. This extension of the subarachnoid space around the penetrating arteries and draining veins is called the Virchow–Robin space. The fluid within this space is CSF.

The Pia

This, the last and deepest layer of the meninges, is a thin layer closely applied to the surface of the brain.

The Visible Outer Surface of the Brain

The outermost part of the brain surface is composed of a thin mantle of cortex. The cortex is made up of cells, both neurons and their supporting elements of several different cell types, all collectively referred to as glial cells. Because in the fresh brain the neurons on the surface appear gray, the cortex is also referred to as gray matter. Just below the cortex, the tissue that is the axons of neurons – each one surrounded by a fatty sheath – interconnects different portions of the brain. Since these nerve sheaths appear “white” in the fresh brain, they are referred to as white matter. The cellular organization of the brain will be discussed in more detail in the section on the cerebral hemispheres, below.

The Imaging Appearance of the Normal Scalp, Skull, and Meninges

In general, different elements of the scalp, skull and meninges show up differently on the two major imaging methods: CT and MR. CT demonstrates bony structures better than MR scans. MR is superior in the demonstration of the soft tissues of the scalp superficially and of the meningeal structures that are deep to the cranium. On CT, beginning most superficially in the scalp, a thin, dense (bright) line represents the skin or dermis. Deep to this is a predominantly fat layer of variable thickness that has low density – a CT number of less than zero (for more information on CT numbers, see the introduction to CT at the beginning of Chap. 2). Immediately deep into the subcutaneous fatty tissue is another dense, fibrous layer that is intimately applied to the outer surface of the skull. Due to its thinness, this structure is usually not discretely imaged. The thick, protective top and sides of the skull consist of both an inner and an outer layer (or table) of dense bone, which appear on CT as an inner and an outer white line, separated by an interposed lower density, more lucent (darker) line that is the diploic or marrow space. The contents of the diploic space are cellular and may represent fatty marrow, and thus the CT numbers can be fairly low. Even if a contrast agent is administered, it is difficult to image the dura on the inner surface of the inner table. Similarly, the pia and arachnoid are not easily visualized on CT scanning. The subarachnoid space, with the black (i.e., low density) CSF filling